



Temperature trends for coastal and adjacent higher lying interior regions of KwaZulu-Natal, South Africa

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Received: 3 October 2017 / Accepted: 15 August 2018 / Published online: 25 August 2018
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Abstract

Temperature trends for KwaZulu-Natal (KZN), South Africa, are investigated for the period 1930–2015, with the intention to test whether interior regions (within ~ 100 km of the coast) are warming faster than coastal regions, given oceanic moderating effects along the coast. This is achieved through analyzing instrumental temperature records from the coastal station of Mount Edgecombe, and adjacent interior stations of Cedara and Emerald Dale. The modified Mann-Kendall test is used to determine annual and seasonal mean temperature (\bar{T}), maximum temperature (T_{\max}), and minimum temperature (T_{\min}) trends for the period 1930–2015, and for the most recent few decades. For annual T_{\max} , a significant increasing trend (0.07 °C/decade) is recorded at the coast, whereas adjacent interior stations record no trend. Annual T_{\min} record significant warming at all stations, with warming rates over the interior being double that recorded at the coast for the period 1930–2015. For seasonal T_{\min} over the interior, significant warming rates are recorded: 0.21 °C/decade (summer), 0.22 °C/decade (autumn), 0.20 °C/decade (winter), and 0.15 °C/decade (spring). Seasonal T_{\min} warming over the coast were also significant: 0.16 °C/decade (summer), 0.08 °C/decade (autumn), 0.06 °C/decade (winter), and 0.12 °C/decade (spring). Thus, higher lying interior regions are warming at considerably greater magnitudes compared to adjacent coastal areas, mainly due to T_{\min} warming trends. For the period 1930–2015, record positive annual T_{\max} anomalies are reported for 2015 at Mount Edgecombe (mean anomaly = 1.6 °C), Cedara (mean anomaly = 1.7 °C), and Emerald Dale (mean anomaly = 2.0 °C).

Keywords Temperature · Trends · Mann-Kendall · KwaZulu-Natal · Coastal

1 Introduction

Globally, there has been much focus on recent decadal trends in continental and sea surface temperatures (SSTs) (Santos et al. 2012), yet relatively few studies have investigated trends for the geographic boundary between these major global regions (i.e., coastal and adjacent interior zones), with consequent uncertainties remaining (Baumann and Doherty 2013).

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00704-018-2602-6>) contains supplementary material, which is available to authorized users.

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Although coastal regions (located in close proximity to the sea) only represent ~2% of global land area, these host ~10% of the world's population and ~13% of urban population (McGranahan et al. 2007). Coastal zones are recognized as vulnerable to global warming given their exposure to consequent sea-level rise and increased storm surges (McGranahan et al. 2007). To this end, establishing recent past climate-thermal trends in coastal and adjacent higher lying interior regions is important for associated adaptive planning and risk preparedness.

Notably, some studies have measured mean annual cooling trends during recent decades along several coastlines (e.g., some portions of the North and South American west coast; east coast of Canada), while higher elevation adjacent interior regions recorded strongly diverging warming trends (e.g., Morgan et al. 1993; Falvey and Garreaud 2009; Lebassi et al. 2009). In contrast, very strong warming is recorded along the west coast of Greenland, particularly during the last 10–20 years, while weaker warming has occurred on the east Greenland coast for the period 1881–2012 (Hanna et al.

2012). Similarly, significant increasing annual mean temperature (\bar{T}) has been observed along the Mediterranean coast (0.22–0.46 °C/decade) and at inland (0.27–0.42 °C/decade) stations in Israel for the period 1970–2002 (Kafle and Bruins 2009).

In the African context, the mean annual maximum temperature (T_{\max}) in Libya recorded increasing trends at five of its nine coastal stations (0.18–0.21 °C/decade) and four of its six inland stations (0.14–0.24 °C/decade) for the period 1945–2009. For the same period, annual \bar{T} increases were observed at all (nine) coastal stations (0.13–0.29 °C/decade), and at all six inland stations (0.03–0.43 °C/decade). Strong \bar{T} seasonal warming trends are recorded at inland stations (autumn 0.27 °C/decade, winter 0.14 °C/decade, spring 0.23 °C/decade, and summer 0.30 °C/decade) and at the coast (autumn 0.25 °C/decade, winter 0.14 °C/decade, spring 0.17 °C/decade, and summer 0.19 °C/decade) (Ageena et al. 2014). This indicates greater warming rates for autumn, spring, and summer over the interior compared to the coast. In southern Africa, temperature trends for coastal and lake areas along the Mozambique channel regions for the period 1939–1992 indicate daytime warming and night time cooling trends, while the northern part of eastern Africa inversely recorded nighttime warming and daytime cooling during the same time (King'uyu et al. 2000).

Although some work has focused on recent decadal temperature changes in South Africa (e.g., Kruger and Shongwe 2004; MacKellar et al. 2014), there has not been a specific focus investigating trends along coastal regions. The only exception is an earlier study (Jury 1998) which demonstrated quasi-cyclical temperature trends for the period 1960–1997 at four coastal stations (Port Shepstone, Durban, Mount Edgecombe, and St Lucia) in KwaZulu-Natal (KZN). Although Kruger and Shongwe (2004) established that stations with significant mean annual T_{\max} positive trends are mainly located in coastal regions, such findings have not been directly contrasted with those for adjacent inland regions. In addition, previous South African work establishing temperature trends has focused mainly on the last half century (e.g., Kruger and Shongwe 2004; MacKellar et al. 2014). However, most recently, Lakhraj-Govender et al. (2017) emphasized the importance of working from longer temporal records and established significant increasing temperature trends over the Western Cape Province for the period 1916–2013. While Kruger and Nxumalo (2017) also recently established long-term temperature trends for the period 1931–2015 across parts of South Africa, the study used absolute homogenization procedures, which do not use a reference series for the adjustment of the series. These methods typically decrease the homogeneity of data for monthly and annual means (Venema et al. 2012). Kruger and Nxumalo (2017) confirm somewhat dubious results following time series adjustments, with a large number of inhomogeneities, which prior to homogenization

produced strong trends. This demonstrates the risk of using absolute homogenization. Therefore, our study uses relative homogenization methods to produce high-quality datasets. Homogenization testing techniques are used to identify artificial bias in time series as a result of nonclimatic factors such as station relocation, instrumentation changes, and urbanization, to name a few (Kenawy et al. 2013). Relative homogenization methods create a reference series constructed from neighboring stations, which enables the detection of change points and adjustment of the time series (Kenawy et al. 2013). Despite no uniform global warming trend between coastal and adjacent interior regions, as demonstrated above, it is hypothesized that interior warming has been greater than that along the KZN coast, given likely coastal moderating effects. Hence, to test this hypothesis, the aim is to examine temperature trends for KZN for the period 1930–2015, with a specific focus on comparing coastal and adjacent (within ~100 km) higher lying interior regions.

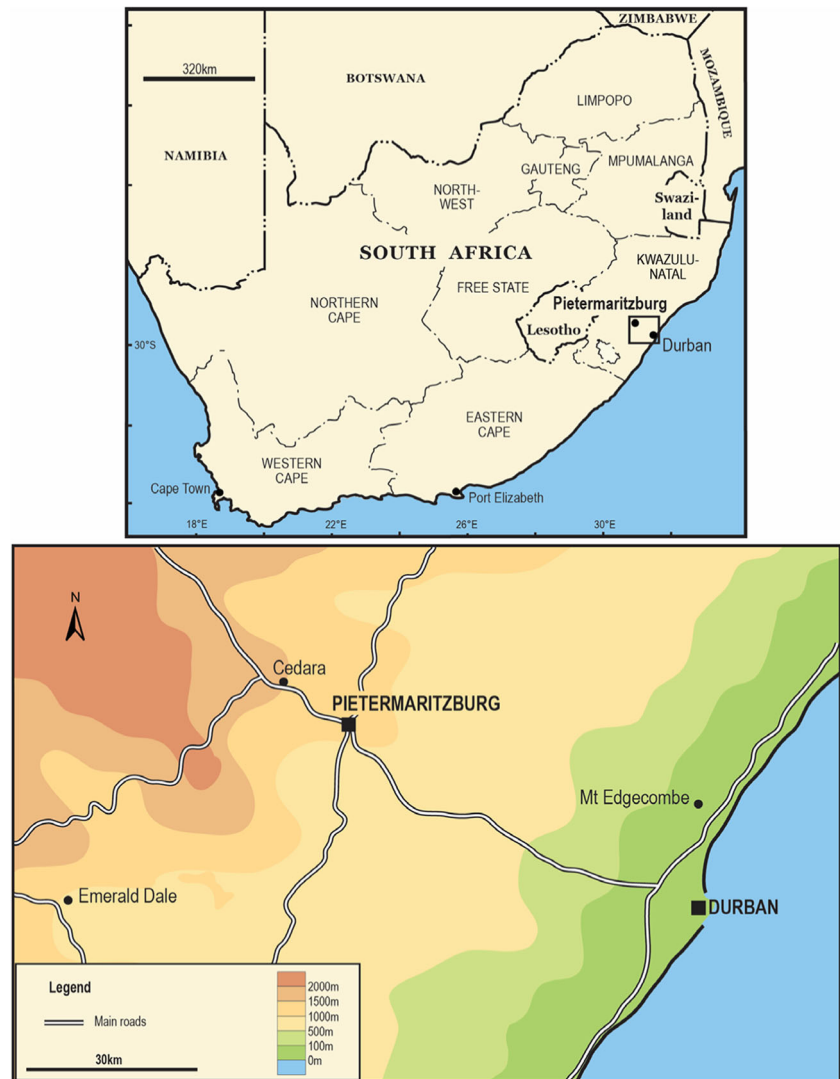
2 Region and its climate

KZN is a province situated along the southeast coast of South Africa. It has a varied topography with relatively flat coastal plain in the east, rising gradually westward toward the so-called midlands and more substantially ~200 km inland on reaching the Drakensberg (Main Escarpment) (Fig. 1) (Eeley et al. 1999). KZN's climate is strongly influenced by the Indian Ocean, and particularly the warm Agulhas current (Reason 2001; Green et al. 2012), hence accounting for high humidity, temperatures, and summer rainfall. Tropical temperate troughs, east coast low-pressure systems, and southeast coast ridging high-pressure systems dominate during austral summer and spring (Tyson and Preston-Whyte 2000). The anticyclone belt weakens and shifts southward, allowing the tropical easterly flow to influence weather during summer. Near surface low-pressure systems dominate during summer, when moisture from the tropics is transported to the region (Landman et al. 2009). During winter, moisture from the tropics is reduced by the northward migration of the Intertropical Convergence Zone (ITCZ) and the intensification of the anticyclonic circulation, hence limiting precipitation. However, perturbations in the westerly circulation, in the form of anticyclones, as well as ridging high-pressure systems behind cold fronts, dominate during winter (Tyson and Preston-Whyte 2000).

3 Data sources

In an attempt to avoid latitudinal climatic influence, this study only focuses on stations located within a narrow latitudinal band (29.5–29.9S) in KZN. This is achieved through an analysis of instrumental temperature records available for the

Fig. 1 Map showing KwaZulu-Natal stations (black solid dots), South Africa



coastal station of Mount Edgecombe, and inland stations of Cedar and Emerald Dale (Fig. 1). Raw daily T_{\max} and T_{\min} values for various KZN stations were selected based on available long-term temperature data and quality/completeness of the dataset. Daily T_{\max} and T_{\min} for the stations (i.e., Cedar, Emerald Dale, and Mount Edgecombe) were obtained electronically from the South African Weather Service (SAWS) (Table 1). Mean monthly T_{\max} and T_{\min} data for Cedar (1957) and Mt. Edgecombe (September 1947–December 1947, 1959) were digitized from the Department of Transport Meteorological Data Reports, sourced from the NOAA Central Library (2013).

Department of Transport Meteorological Data Reports indicate that the Cedar station relocated on 4 November 1969 (by 274.3 m horizontally and losing 9 m altitudinally) and the Emerald Dale station became a third-order station (i.e., records only T_{\max} and T_{\min} at 08:00) on 1 August 1969 (NOAA Central Library 2013). According to station history reports, the Mount Edgecombe station changed to an

automatic station on 1 October 1992 and Cedar was converted to an automatic station on the 1 September 2005. However, no change points were detected at these stations for the aforementioned dates (Appendix Table A).

4 Methodology

Daily temperature data were quality controlled with RClimDex to identify manual keying errors and check for coherency between maximum and minimum values. Outliers were identified using the ProClimDB interquartile range. The standard normal homogeneity test (SNHT) and bivariate tests (in AnClim software) were employed to detect artificial biases or inhomogeneities in the time series. ProClimDB software was used to create the reference series and adjust the time series (Štěpánek et al. 2011). The homogenization procedure is more extensively detailed in Lakhraj-Govender et al. (2017)

Table 1 KwaZulu-Natal station details with start/end dates for temperature recording

Station name	Latitude (deg. S)	Longitude (deg. E)	Altitude (m a.s.l.)	Dist. from the coast (km)	Start date	End date
Cedara	−29.54°	30.27°	1071	83.3	1930/01/01	2015/12/31
Mount Edgecombe	−29.70°	31.05°	103	5.6	1930/01/01	2015/12/31
Emerald Dale	−29.94°	29.96°	1189	86.5	1930/01/01	2015/12/31

and Appendix A. Notably, \bar{T} , T_{\max} , and T_{\min} time series were separately adjusted for detected inhomogeneities. For the period 1930–2015, monthly \bar{T} , T_{\max} , and T_{\min} anomalies were calculated, relative to the 1961–1990 mean. Seasonal means are defined as austral summer (December, January, and February), autumn (March, April, and May), winter (June, July, and August), and spring (September, October, and November). The modified Mann-Kendall (MK) test was used to identify possible annual and seasonal \bar{T} , T_{\max} , and T_{\min} trends at Mount Edgecombe, Cedara, and Emerald Dale for the full period (1930–2015), as well as the most recent 31-year (1985–2015) period. To remove serial autocorrelation expected in the data, the modified version of the MK test was used (Yue and Wang 2004). The MK test statistic (S) is initially assumed to be 0 (i.e., no trend). S increases (decreases) by 1 if a later datum is higher (lower) than the datum from the earlier time. The net result of increases and decreases, yields the final S value (Shahid et al. 2012) which indicates the magnitude of temperature trends, while the sign denotes whether the trend is increasing or decreasing. Statistical significance of the trend is based on the MK Z test statistic, calculated from the variance of S . Positive Z values indicate increasing trends while negative values are decreasing trends (Gocic and Trajkovic 2013). At the 5% significance level, if $Z > 1.96$ or $Z < -1.96$, the trend is significant.

Magnitudes of the trends were determined using Sen's nonparametric slope estimator (Q) (Sen 1968). If the probability (p value) is less than the chosen significance level ($\alpha = 0.05$), then the null hypothesis (H_0 , i.e., no trend in the series) must be rejected and the alternative hypothesis (H_a , i.e., there is a trend) accepted (XLStat 2015). The slope is statistically different from zero for the selected confidence interval (95%) if the upper (Q_{\max}) and lower (Q_{\min}) limits have similar signs (Gocic and Trajkovic 2013). AnClim software (Štěpánek 2008) was used to produce a 10-year Gaussian low-pass filter, which smoothens annual average temperature and exhibits decadal temperature variability. This low-pass filtering does not apply to all subsequent results. Trends are not based on low-pass filtered data; hence, the significance of the total trend results is not affected. Data were discarded for the period 2004–2006 at Mount Edgecombe, because the quality control in RClimDex software flagged unusual daily values during these years. The software also detected instances where

T_{\max} was equal to T_{\min} and was thus deemed unsuitable for use. The software employs a user-defined standard deviation of 4.

5 Results

5.1 Temperature trends for the period 1930–2015

For the period 1930–2015, annual \bar{T} marginally increases at Mount Edgecombe (0.07 °C/decade) and Cedara (0.08 °C/decade), while no trend is recorded for Emerald Dale. Although the S value for Emerald Dale increases and Q is 0.03, the trend cannot be regarded as increasing because the p value is greater than 0.05 and the Z value is less than 1.96. Annual T_{\max} slightly increases at Mount Edgecombe (0.07 °C/decade) while inland stations record no trend at Cedara and at Emerald Dale. Highly significant annual T_{\min} warming rates occur at inland stations (i.e., Cedara = 0.24 °C/decade; Emerald Dale = 0.15 °C/decade), while that for the coastal station of Mount Edgecombe is somewhat lower (0.10 °C/decade) (Table 2).

For the period 1930–2015, \bar{T} record significant increasing trends during all seasons at Mount Edgecombe. No trend is observed at Emerald Dale and Cedara during winter, while significant increasing trends are recorded for summer at Cedara (0.14 °C/decade) and Emerald Dale (0.09 °C/decade). T_{\max} record significant warming during autumn and winter (0.09 °C/decade and 0.1 °C/decade, respectively) at Mount Edgecombe and decreasing trends during all seasons at Emerald Dale, but significant during only spring. At Cedara, T_{\max} also records a significant decreasing trend (−0.08 °C/decade) during spring, while the remaining seasons record warming trends. For the period 1930–2015, T_{\min} record significant warming trends (0.05–0.34 °C/decade) during all seasons at all three stations, with greatest warming during autumn (0.26 °C/decade) and winter (0.34 °C/decade) at Cedara (Table 2).

5.2 Temperature trends for the period 1985–2015

Temperature trends for the most recent decades (~30 years) are often determined for comparison with those for previous periods (e.g., Rebetz and Reinhard 2008; Sonali and Kumar

Table 2 Annual and seasonal \bar{T} , T_{max} and T_{min} Mann Kendall statistics and Sen's slope estimate (Q) (°C/decade) at KZN stations. Seasonal definitions used: summer = DJF, autumn = MAM, winter = JJA and spring = SON

	\bar{T}				T_{max}				T_{min}			
	<i>S</i>	<i>Q</i>	<i>Z</i>	<i>p</i> -value	<i>S</i>	<i>Q</i>	<i>Z</i>	<i>p</i> -value	<i>S</i>	<i>Q</i>	<i>Z</i>	<i>p</i> -value
Annual												
1930-2015												
Mount Edgecombe	1141	0.09	3.7	0.003	658	0.07	2.1	0.040	754	0.10	6.2	0.10
Cedara	1467	0.13	7.9	<0.0001	98	0.01	0.4	0.683	2483	0.24	19.8	0.24
Emerald Dale	341	0.03	1.1	0.396	-446	-0.08	-1.4	0.166	1690	0.15	17.7	0.15
1985-2015												
Mount Edgecombe	154	0.20	5.7	< 0.0001	152	0.32	8.0	< 0.0001	84	0.14	2.5	0.011
Cedara	135	0.23	6.2	0.000	123	0.32	5.4	<0.0001	143	0.19	5.1	< 0.0001
Emerald Dale	129	0.30	4.4	< 0.0001	117	0.40	3.1	0.002	109	0.21	3.9	< 0.0001
Seasonal												
Mount Edgecombe												
Summer	1271	0.14	6.1	< 0.0001	759	0.1	3.1	0.02	1449	0.16	9.7	< 0.0001
Autumn	836	0.09	3.7	0.000	695	0.09	2.4	0.02	634	0.08	5.3	< 0.0001
Winter	671	0.09	2.5	0.01	583	0.10	2.3	0.02	583	0.06	2.3	<0.0001
Spring	783	0.08	3.1	< 0.0001	240	0.03	1.0	0.34	1283	0.12	7.7	< 0.0001
Emerald Dale												
Summer	661	0.07	2.9	< 0.0001	-423	-0.08	-1.4	0.17	1844	0.22	12.7	< 0.0001
Autumn	499	0.07	2.3	0.45	-338	-0.08	-1.1	0.27	1436	0.17	10.0	< 0.0001
Winter	197	0.02	0.9	0.8	-160	-0.03	-0.7	0.47	601	0.05	3.8	0.000
Spring	-352	0.02	-0.6	0.006	-630	-0.15	-2.2	0.03	998	0.12	12.5	< 0.0001
Cedara												
Summer	1242	0.12	8.8	< 0.0001	336	0.04	2.1	0.03	1967	0.19	22.9	< 0.0001
Autumn	1273	0.14	9.3	< 0.0001	212	0.03	1.2	0.23	1882	0.26	16.5	< 0.0001
Winter	1658	0.22	18.9	0.5	603	0.09	4.6	< 0.0001	2171	0.34	20.0	< 0.0001
Spring	369	0.04	1.9	0.12	-488	-0.08	-2.2	0.03	1610	0.17	18.6	< 0.0001

Mann Kendall test statistic (*S*) = the strength of the temperature trend; sign indicates increasing or decreasing trend. *Z* test statistic = statistical significance of the trend, calculated from the variance of *S*. If $Z > Z_{1-\alpha/2}$, at the chosen level of significance $\alpha = 0.05\%$, where *Z* greater than 1.96, the trend is significant (bold) (Gocic and Trajkovic 2013). When the *p* value is lower than the chosen significance level, $\alpha = 0.05$, the null hypothesis (no trend in the series) is rejected and the alternative hypothesis (there is a trend) is accepted (XLStat 2015)

2013; Ageena et al. 2014). For the period 1985–2015, annual \bar{T} significantly increases by 0.20 °C/decade at Mount Edgecombe, 0.23 °C/decade at Cedara, and 0.30 °C/decade at Emerald Dale. This is largely owing to significant increases in annual T_{max} at all stations: by 0.32 °C/decade at Mount Edgecombe, 0.32 °C/decade at Cedara, and 0.40 °C/decade at Emerald Dale. Over the same period, annual T_{min} at Mount Edgecombe significantly increased by 0.14 °C/decade, and at inland stations significantly warmed by 0.19 °C/decade at Cedara and 0.21 °C/decade at Emerald Dale (Table 2).

5.3 Decadal temperature variability

A 10-year Gaussian filter was applied to the annual temperature, to establish whether decadal variability was different/similar at coastal and adjacent interior stations. For \bar{T} at

Mount Edgecombe, the low-pass filter records cooler periods between 1930 and 1990, but subsequently, positive anomalies (from the 1961–1990 mean) have been recorded. At inland stations, Cedara records mostly negative temperature anomalies for the period 1960–1981, and above mean conditions since 1981 (with few exceptions; Fig. 2). The 10-year low-pass filter for T_{max} indicates broadly warmer times between 1930 and 1963, cooler (below mean) conditions between 1964 and 1975, and a warming trend since 1977 at Mount Edgecombe. A broadly warmer period between 1930 and 1962 is observed at Cedara, followed by below mean conditions until 1981, and thereafter oscillates above average until the end of the record. At Emerald Dale, above mean conditions prevail between 1930 and 1950, with a cooler period until 1982. The most recent decades show smaller T_{max} oscillations for inland stations, with short cooler (below mean) periods between 1987–1991 and 1995–1998. Notably, such

cooler episodes are not as prominent at Mount Edgecombe (Fig. 2). While coastal T_{\max} values remained above the long-term mean since ~ 1977 , this has been delayed at adjacent inland sites by ~ 21 (Cedara) to 33 years (at Emerald Dale).

The Gaussian filters for T_{\min} indicate a broadly cooler period from 1930–1984 at Mount Edgecombe, 1930–1981 at Cedara, and 1930–1973 at Emerald Dale. Thereafter, positive anomalies are recorded at Cedara (1982–2015) and at Emerald Dale (1974–2015). Mount Edgecombe experiences short periods of above (1985–1988) and below (1989–1997) mean anomalies, a warmer period from 1999 to 2012, and slight cooling towards the end of the record (Fig. 2).

6 Discussion

The Northern and Southern Hemispheres experienced warming trends from ~ 1910 to the mid-1940s, followed by cooler/variable temperatures between 1940 and mid-1970s, and thereafter rapid (Northern Hemisphere) and gradual (Southern Hemisphere) warming (Jones et al. 1986, 2016). For southern Africa, Kruger and Shongwe (2004) report that mean annual temperatures start increasing during the early 1980s. While the current study records the start of \bar{T} warming at a similar time over the interior

(1981 at Cedara), warming at the coast was delayed by a decade (1991 at Mount Edgecombe).

Several studies report coastal cooling and strong interior warming over North and South America (Morgan et al. 1993; Falvey and Garreaud 2009; Lebassi et al. 2009). Lebassi et al. (2009) suggest coastal cooling may be due to greenhouse gas induced global warming over the interior which results in increased sea breeze flow, thus overwhelming warming along the coast. Elsewhere, such as along the Canadian east coast and Mediterranean south coast, coastal warming has generally been slower than over the adjacent interior (Kafle and Bruins 2009; Tyler et al. 2015). For the observed data, the current study finds only a marginally greater magnitude of warming (by $0.01\text{ }^{\circ}\text{C}$) over parts of the KZN interior compared to the coast during the past 85 years. However, more noteworthy is that annual T_{\max} and T_{\min} have increased at greater magnitudes (by $0.04\text{ }^{\circ}\text{C}/\text{decade}$ and $0.06\text{ }^{\circ}\text{C}/\text{decade}$, respectively) over the interior compared to the coast during the most recent 31 years, suggesting that spatial contrasts in the rate of climate warming have increased during the most recent decades. Previous studies have suggested that coastal cooling may result from increased coastal upwelling, cloud cover, or sea breezes (Lebassi et al. 2009). Smaller magnitudes of warming along coastal KZN may possibly be due to the moderating influence of the Agulhas current (Tyson and Preston-Whyte 2000).

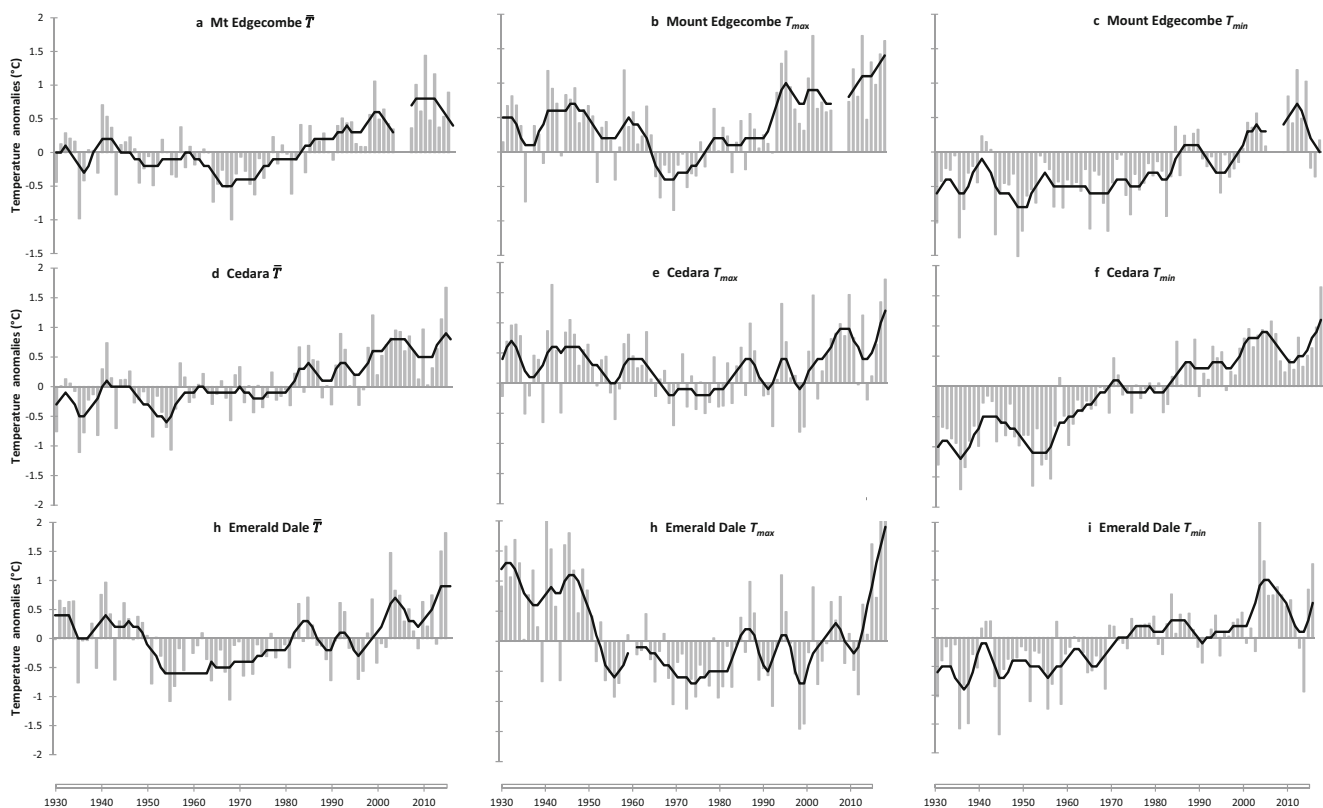


Fig. 2 Annual \bar{T} , T_{\max} , and T_{\min} anomalies, with respect to the long term mean (1961–1990) for KZN stations, with the low pass filter (black solid line)

The Agulhas current influences coastal weather and climate and creates coastal upwelling. Coastal upwelling occurs when along-shore winds force offshore transport of surface water, leading to a rise of cooler and nutrient rich water. Along the continental slope of Durban, coastal upwelling brings cold water from depths of 400 m (Goschen et al. 2015). Large solitary meanders of the Agulhas current (30–300 km; referred to as “Natal Pulses”), occurring 0–6 times per annum, develop off KwaZulu-Natal and substantially influence the structure of the coastal ocean in this region (Goschen et al. 2015). Natal Pulses are associated with a cold-water core and a cyclonic circulation inshore of the current. In addition, Natal Pulses strongly influence coastal and shelf regions where they drive localized upwelling (Rouault and Penven 2011). According to Rouault and Penven (2011), the size and frequency of Natal Pulses increased over the period June 2004 to October 2010. Although no further details are available on Natal Pulses since 2010, it is possible that the continued size and frequency of such pulses has contributed towards lowering potential warming rates along the coast. Further research on the strength and frequency of Natal Pulses would, however, be required to confirm this.

Sea surface temperatures (SSTs) in upwelling areas are sensitive indicators of changes in upwelling intensity and prevailing winds (McGregor et al. 2007). Although SSTs significantly increased (0.7 °C/decade) in the Agulhas Current over the period 1980–2006, owing to an increased wind stress curl in the South Indian Ocean (Rouault et al. 2009), a more recent study of global-scale SSTs reports relatively stable seasonal warming off the southeast coast of South Africa (Lima and Wethey 2012). To this end, further investigations are required to determine recent (last few decades) SST trends along the KZN coastline, before any linkages can be made to coastal air temperatures.

The oscillatory temperature characteristics of the current study, denoted by the Gaussian low-pass filter, indicate above average T_{\max} for the period 1930–1962/1963 at the coast and at one inland station (Cedara), with transition to below average conditions occurring much sooner (1952) at Emerald Dale (Fig. 2). The inconsistency between stations clearly indicates that periods of cooler and warmer conditions are controlled by the geography of place, which may differ considerably over relatively short spatial scales. Such inconsistencies are also noted in the seasonal trends at all stations, for the period 1930–2015. Similarly, Kruger and Shongwe (2004) recorded locational and seasonal variations in South African temperature trends for the period 1960–2003. A previous study reported increasing annual \bar{T} , T_{\max} , and T_{\min} trends at coastal and adjacent interior stations in KZN for the period 1960–2003, with the exception of decreasing \bar{T} and T_{\max} trends at Emerald Dale (Kruger and Shongwe 2004). \bar{T} , T_{\max} , and T_{\min} record increasing trends during all seasons at the coast. However,

over the interior of KZN, variable seasonal trends are recorded between stations, with no \bar{T} trends during winter and decreasing T_{\max} trends during spring. For seasonal T_{\min} over the interior, significant warming rates are recorded: 0.21 °C/decade (summer), 0.22 °C/decade (autumn), 0.20 °C/decade (winter), and 0.15 °C/decade (spring). Seasonal T_{\min} warming over the coast were also significant: 0.16 °C/decade (summer), 0.08 °C/decade (autumn), 0.06 °C/decade (winter), and 0.12 °C/decade (spring). Increasing magnitudes of warming rates with time have been reported for the most recent decades over both hemispheres (Rebetez and Reinhard 2008). Similarly, this study also records an increased magnitude of warming trends for the most recent decades compared to previous periods over KZN, South Africa.

Finally, high positive T_{\max} anomalies are noted at Cedara for the years 1985 (mean anomaly = 1.0 °C), 1992 (mean anomaly = 1.3 °C), 1999 (mean anomaly = 1.5 °C), and 2015 (mean anomaly = 1.7 °C), coincidentally at 7-year intervals for the first two periods and at 8-year intervals for the following two periods. The highest recorded annual T_{\max} anomalies at Mount Edgecombe (mean anomaly = 1.6 °C), Cedara (mean anomaly = 1.7 °C), and Emerald Dale (mean anomaly = 2 °C) also reflect amplified warming/anomalies over the interior compared to the coast.

7 Conclusion

This paper establishes differences in rates of warming between coastal and adjacent (within ~ 100 km) higher lying interior regions of KZN for the period 1930–2015. The most notable finding is the considerable recent increase in magnitude of annual and seasonal warming at relatively high lying interior regions, compared to the adjacent coastal areas over the last 31 years in particular. Slower rates of warming along the coast may be owing to oceanic moderating effects, such as those associated with the Agulhas current (e.g., Natal Pulses), but these require further investigation. The complexities of synergistically operating climate mechanisms (i.e., anthropogenically induced CO₂ warming or ENSO), and the interaction of these factors and how they collectively influence each another (and ultimately the spatio-temporal differences in regional warming), requires further research to be better understood. Nonetheless, it seems that climate warming trends over relatively small subregional scales may continue at disproportionate rates in some global regions, such as coastal and adjacent hinterland regions, especially where these patterns of warming might reinforce or alter local airflow dynamics. Determining the nature of temperature trends at a fine scale is thus important for appropriate site-specific future preparedness and planning.

Acknowledgements The authors wish to thank SAWS for providing temperature data. RL-G appreciates the Department of Higher Education and Training Research Development Grant provided by the Tshwane University of Technology (TUT), South Africa, and the National Research Foundation (NRF) of South Africa (98258).

References

- Ageena I, Macdonald N, Morse AP (2014) Variability of maximum and mean average temperature across Libya (1945–2009). *Theor Appl Climatol* 117:549–563. <https://doi.org/10.1007/s00704-013-1012-z>
- Baumann H, Doherty O (2013) Decadal changes in the world's coastal latitudinal temperature gradients. *PlosOne* 8:e67596. <https://doi.org/10.1371/journal.pone.0067596>
- Eeley HAC, Lawes MJ, Piper SE (1999) The influence of climate change on the distribution of indigenous forest in KwaZulu-Natal, South Africa. *J Biogeogr* 26:595–617
- Falvey M, Garreaud RD (2009) Regional cooling in a warming world: recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). *J Geophys Res* 114:1–16. <https://doi.org/10.1029/2008JD010519>
- Gocic M, Trajkovic S (2013) Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Glob Planet Chang* 100:172–182. <https://doi.org/10.1016/j.gloplacha.2012.10.014>
- Goschen WS, Bornman TG, Deyzel SHP, Schumann EH (2015) Coastal upwelling on the far eastern Agulhas Bank associated with large meanders in the Agulhas Current. *Cont Shelf Res* 101:34–46
- Green AN, Ovechikina MN, Mostovski MB (2012) Late Holocene shore face evolution of the wave dominated Durban Bight, KwaZulu-Natal, South Africa: a mixed storm and current driven system. *Cont Shelf Res* 49:56–64. <https://doi.org/10.1016/j.csr.2012.09.003>
- Hanna E, Mernild SH, Cappelen J, Steffen K (2012) Recent warming in Greenland in a long-term instrumental (1881–2012) climatic context: I. Evaluation of surface air temperature records. *Environ Res Lett* 7:1–16. <https://doi.org/10.1088/1748-9326/7/4/045404>
- Jones PD, Raper SCB, Wigley TML, Diaz HF, Kelly PM, Wigley TML (1986) Northern Hemisphere surface air temperature variations: 1851–1984. *J Clim Appl Meteorol* 25:161–179
- Jones PD, Parker DE, Osborn TJ, Briffa KR (2016) Global and hemispheric temperature anomalies—land and marine instrumental records. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi: <https://doi.org/10.3334/CDIAC/cli.002> <http://cdiac.ess-dive.lbl.gov/trends/temp/jonescru/jones.html> Accessed 31 July 2018
- Jury MR (1998) Statistical analysis and prediction of KwaZulu-Natal climate. *Theor Appl Climatol* 60:1–10
- Kafle HK, Bruins HJ (2009) Climatic trends in Israel 1970–2002: warmer and increasing aridity inland. *Clim Chang* 96:63–77
- Kenawy AE, Lopez-Moreno JI, Štěpánek P, Vicente-Serrano SM (2013) An assessment of the role of homogenization protocol in the performance of daily temperature series and trends: application to north-eastern Spain. *Int J Climatol* 33:87–108
- King'uyu SM, Ogallo LA, Anyamba EK (2000) Recent trends of minimum and maximum surface temperatures over Eastern Africa. *J Clim* 13:2876–2886
- Kruger AC, Nxumalo M (2017) Surface temperature trends from homogenized time series in South Africa: 1931–2015. *Int J Climatol* 37:2364–2377
- Kruger AC, Shongwe S (2004) Temperature trends in South Africa: 1960–2003. *Int J Climatol* 24:1929–1945. <https://doi.org/10.1002/joc.1096>
- Lakhraj-Govender R, Grab S, Ndebele NE (2017) A homogenized long-term temperature record for the Western Cape Province in South Africa: 1916–2013. *Int J Climatol* 37:2337–2357
- Landman WA, Kgatuke MJ, Mbedzi M, Beraki A, Bartman A, du Piesanie A (2009) Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *Int J Climatol* 29:1535–1549
- Lebassi B, Gonzalez J, Fabris D, Maurer E, Miller N, Milesi C, Bornstein R (2009) Observed 1970–2005 cooling of summer daytime temperatures in coastal California. *J Clim* 22:3558–3573
- Lima FP, Wetthey DS (2012) Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nat Commun* 704:1–13. <https://doi.org/10.1038/ncomms1713>
- MacKellar N, New M, Jack C (2014) Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. *S Afr J Sci* 110:1–13. <https://doi.org/10.1590/sajs.2014/20130353>
- McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ Urban* 19:17–37
- McGregor HV, Dima M, Fischer HW, Mulitza S (2007) Rapid 20th century increase in coastal upwelling off Northwest Africa. *Science* 315:637–639. <https://doi.org/10.1126/science.1134839>
- Morgan MR, Drinkwater KF, Pocklington R (1993) Temperature trends at coastal stations in eastern Canada. *Climatol Bull* 27:135–153
- NOAA central library (2013) Department of Transport Reports on Meteorological data (1920–1977) The government printer, Pretoria. Available online <https://library.noaa.gov/Collections/Digital-Docs/Foreign-Climate-Data/South-Africa-Climate-Data>. Accessed 22 July 2016
- Reason CJC (2001) Evidence for the influence of the Agulhas Current on regional atmospheric circulation patterns. *J Clim* 14:2769–2778
- Rebetez M, Reinhard M (2008) Monthly air temperature trends in Switzerland 1901–2000 and 1975–2004. *Theor Appl Climatol* 91:27–34. <https://doi.org/10.1007/s00704-007-0296-2>
- Rouault MJ, Penven P (2011) New perspectives on Natal Pulses from satellite observations. *J Geophys Res* 116:C07013. <https://doi.org/10.1029/2010JC006866>
- Rouault MJ, Penven P, Pohl B (2009) Warming in the Agulhas Current since 1980s. *Geophys Res Lett* 36:L12602. <https://doi.org/10.1029/2009GL037987>
- Santos F, Gomez-Gesteira M, de Castro M, Alvarez I (2012) Variability of coastal and ocean water temperature in the upper 700 m along the western Iberian Peninsula from 1975 to 2006. *PlosOne* 7:1–7. <https://doi.org/10.1371/journal.pone.0050666>
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63:1379–1389
- Shahid S, Harun SB, Katimon A (2012) Changes in diurnal temperature range in Bangladesh during the time period 1961–2008. *Atmos Res* 118:260–270. <https://doi.org/10.1016/j.atmosres.2012.07.008>
- Sonali P, Kumar DN (2013) Review of trend detection methods and their application to detect temperature changes in India. *J Hydrol* 476:212–227
- Štěpánek P (2008) AnClim—software for time series analysis. Dept. of Geography, Faculty of Natural Sciences, MU, Brno. <http://www.climahom.eu/AnClim.html>. Accessed 25 June 2015
- Štěpánek P, Zahradníček P, Huth R (2011) Interpolation techniques used for data quality control and calculation of technical series: an example of Central European daily time series. *Időjárás* 115:87–98
- Tyler K, White T, Anslow F (2015) Indicators of climate change for British Columbia 2015 update. Ministry of Environment, Victoria, p 50
- Tyson PD, Preston-Whyte RA (2000) The weather and climate of southern Africa. Oxford University Press Southern Africa, Cape Town
- Venema VKC, Mestre O, Aguilar E, Auer I, Guijarro JA, Domonkos P, Vertacnik G, Szentimrey T, Štěpánek P, Zahradníček P, Viarre J, Muller-Westermeier G, Lakatos M, Williams CN, Menne MJ,

- Lindau R, Rasol D, Rustemeier E, Kolokythas K, Marinova T, Andresen L, Acquaotta F, Fratianni S, Cheval S, Klancar M, Brunetti M, Gruber C, Prohom Duran M, Likso T, Esteban P, Brandsma T (2012) Benchmarking monthly homogenization algorithms. *Clim Past* 7:2655–2718. <https://doi.org/10.5194/cp-8-89-2012>
- XLSTAT (2015) Available online: <https://www.xlstat.com/en/Accessed> 2 January 2015
- Yue S, Wang C (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resour Manag* 18:201–218